UNCERTAINTY QUANTIFICATION IN THE DEVELOPMENT OF AVIATION OPERATIONS TO REDUCE AVIATION EMISSIONS AND CONTRAILS

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Abstract

This paper brings together the modeling of complex aeronautical system behavior and interactions with climate science involving widely varying time (minutes to years) and spatial scales (local to world-wide). The main contributions of the paper are: (a) the integration of simplified models, real weather and traffic data, multiple scenarios and error bounds in a process that can be used to guide operational solutions to reduce the impact of aviation on climate, (b) innovative use of contrail frequency index, a measure of the potential for a specific set of traffic and atmospheric conditions to produce persistent contrails, to reduce the number of computations and (c) the quantification of variation in the fuel cost versus surface temperature reduction curves due to limitations in the modeling of contrail formation, radiative forcing associated with contrails and energy balance models. An important conclusion from the study is that contrail reduction maneuvers involving altitude changes produces more fuel efficient results, measured as decrease in surface temperature change for unit amount of fuel, than just horizontal maneuvers. A 2-3% additional fuel usage reduces the surface temperature change to its lowest value. Any reduction in contrails beyond this point is negated by the increase in CO_2 *emissions. The results suggest that to limit the amount of excess fuel usage while minimizing the environmental impact of aviation operations, it is cost-beneficial to limit contrail reduction maneuvers to days with medium or high amount of contrail formation. These characteristics seem to be true even in the presence of various uncertainties. The quantification results based on this paper can be included in the FAA national policy development tools like Aviation Environmental Design Tool and Aviation Environmental Portfolio Management Tool*

1 Introduction

There is increased awareness of aviation-induced environmental impact affecting climate change [1-2]. It is estimated that aviation is responsible for two to three percent of all anthropogenic Carbon dioxide (CO_2) emissions. The important non-CO_2 impacts associated with aviation are water vapor, Oxides of nitrogen (NOx), condensation trails (contrails) and cirrus clouds due to air traffic. Contrails are clouds that are visible trails of water vapor made by the exhaust of aircraft engines [3]. The latest estimates indicate that contrails caused by aircraft may be causing more climate warming today than all the residual CO_2 emitted by aircraft [4]. Understanding the complexity and uncertainty of the various components of the climate equation requires models, analysis, optimization and validation at several levels.

Modeling and simulation to understand the impact of aviation on climate covers airspace from small regions to the entire world and intervals of time varying from seconds to several hundred years. The modeling of aircraft emissions and their interaction with each other to change the concentration levels of different gasses in the atmosphere and the resulting impact of the radiative forcing on the equilibrium of the Earth's atmosphere is complex and requires the use of coupled atmosphere-ocean general circulation models together with three-dimensional models of carbon cycle and chemistry of other non-CO_2 greenhouse gases. These models are computationally intensive and unsuitable for studies involving the generation of multiple scenarios to study the effect of uncertainties. It is possible to use a hierarchy of models with different levels of accuracy subject to computational limitations and driven by the questions to be answered by the modeling process. Using pre-calculated atmospheric data with aircraft emission data generated by climate-chemistry models, AirClim [5], a climate evaluation tool, reduces the computational time in predicting the evolution of gas concentrations, radiative forcing and temperature changes. The development in this paper is oriented towards detailed models of the airspace operations combined with simple climate models. Simple emission and climate models, based on the input/output relations of linear systems, capture the fundamental emission to climate impact behavior by careful selection of key variables and their dynamics.

The Future Air Traffic Management Concepts Evaluation Tool (FACET) [6], a national level air traffic system simulation and optimization tool, was integrated with aircraft emission models and contrail formation models to create a capability that provides both CO_2 and non-CO_2 emissions resulting from current and future operational concepts and policies. This enables the inclusion of environmental impact metrics as a standard metric/criteria for airspace simulations. However, there is considerable uncertainty about the underlying atmospheric science required to assess the impacts of these emissions, as well as the emissions estimates themselves, in some cases.

The paper presents results on reducing the impact of aviation on climate as a trade-off between the amount of reduction in the changes to the mean surface temperature of the Earth due to CO_2 emissions and contrails and the extra fuel cost associated with the reduction approach. The trade-off curves are generated by solving a series of optimal control problems. The results are based on analyzing a representative set of flights between twelve major city-pairs in the United States. A major contribution of the paper is the study of the sensitivity of fuel cost versus surface temperature reduction curves due to limitations in the modeling of contrail formation, radiative forcing associated with contrails and energy balance models. The policy horizon plays an important role due to the variation in the lifetime of different emissions and contrails. An important conclusion from the study is that contrail reduction maneuvers involving altitude changes produces more fuel efficient results, measured as decrease in surface temperature change for unit amount of fuel, than just horizontal maneuvers. A 2-3% additional fuel usage reduces the surface temperature change to its lowest value. Any reduction in contrails beyond this point is negated by the increase in CO_2 emissions. The results suggest that to limit the amount of excess fuel usage while minimizing the environmental impact of aviation operations, it is cost-beneficial to limit contrail reduction maneuvers to days with medium or high amount of contrail formation. These characteristics seem to be true even in the presence of various uncertainties.

The paper is organized as follows: Section 2 formulates the problem and describes the simulation and optimization methods to generate trade-off curves between changes to the Earth's surface temperature and fuel consumption. The various uncertainties affecting the problem are described in Section 3. Section 4 presents results on the sensitivity of the contrail reduction strategies due to uncertainties in the models. Summary and conclusions are provided in Section 5.

2 Approach

The technical approach used in this paper is illustrated in Figure 1. The method relies on the simulation of national level air traffic scenarios. Aircraft performance models and actual weather data are used to compute various emissions. Contrails and radiative forcing of different types of emissions are modeled using recent advances in climate science. The simulation and optimization of aircraft flights based on safety, capacity, efficiency and environmental impact is a unique feature of the approach. The details

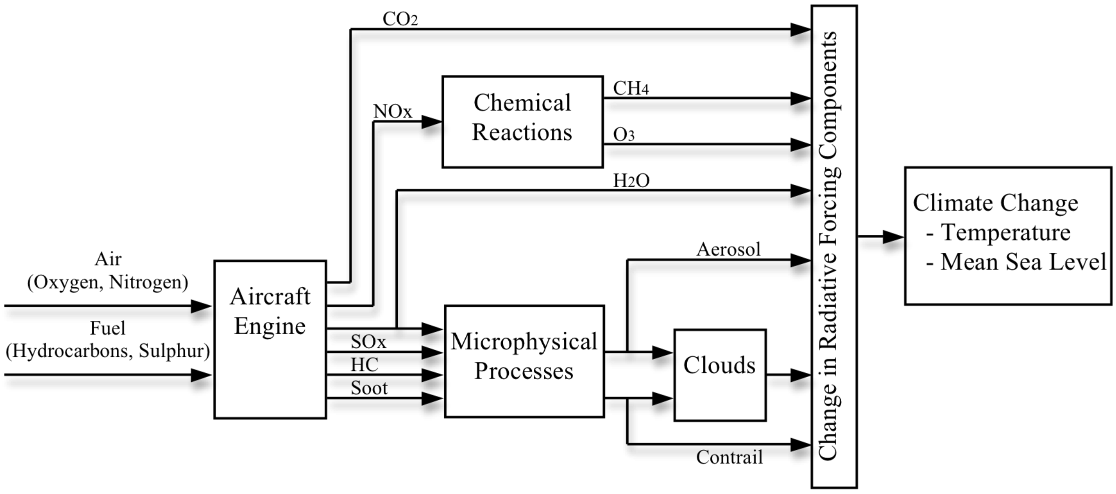


Fig 1. FACET interaction with optimization, emission and contrail models.

about the airspace simulation and aircraft trajectory optimization algorithms are described in [6,7].

Aviation emissions and contrails have very different characteristics and influence the climate either directly or by decomposition into other chemical compounds. CO_2 is the most pervasive of all anthropogenic emissions. The impact of the introduction of additional amount of CO_2 on climate is better understood than the impact of all other greenhouse gases and contrails. In the development of climate metrics, the impact of other emissions is normalized with respect to the impact of CO_2. The atmosphere quickly absorbs additional CO_2 and the CO_2 radiative forcing is due to the globally distributed energy resulting from the uniform increase in CO_2 concentration. Contrails occur at different regions of the earth and add non-uniform sources of energy to the atmosphere. The latest estimates indicate that contrails caused by aircraft may be causing more climate warming today than all the residual CO_2 emitted by aircraft [4]. The lifetime associated with different emissions and contrails varies from a few hours to several hundred years. The impact of certain gases depends both on the amount of emission and the location of the emission. The climate impact is also significantly affected by the time (decision-making horizon) when the impact is estimated. These variations make it necessary to develop a common yardstick to measure the impact of various gases. The difference between different aviation technologies or operational procedures to reduce the impact of aviation on climate can be measured in terms of the differences in near surface temperature changes between the current background scenario and the background scenario modified by new technology or operations. Several climate metrics have been developed to assess the impact of the aviation emissions and develop strategies to limit their impact on the environment. The potential impacts to the climate for the U.S. domestic flights are assessed in terms of mean surface temperature change, referred to as Absolute Global Temperature Potential (AGTP) [8], due to aircraft emissions and persistent contrails formation. The analysis presented in this paper concentrates on the climate impacts of CO_2 emissions and contrails. However, the impact of other emissions can be included in the analysis in a similar manner. The optimal trajectory algorithm is applied to calculate an aircraft trajectory in the presence of winds that minimizes fuel burn and avoids regions of airspace that facilitate persistent contrails formation. Flights between 12 major city-pairs were selected to perform the analysis. The same city-pairs were used by the Federal Aviation Administration to assess the impact of implementation of Reduced Vertical Separation Minima (RVSM) on aircraft-related fuel burn and emissions. This study adapts the standard in RVSM and assumes that the cruising altitudes are between 29,000 and 41,000 feet. Eastbound

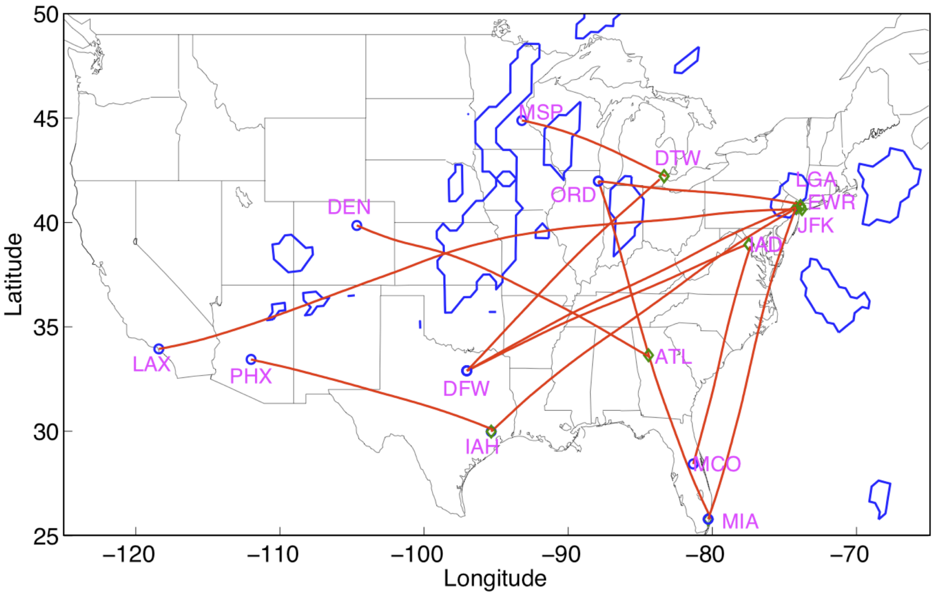


Fig 2. The wind-optimal trajectories for the eastbound flights for 12 city pairs at 37,000 feet, 6 a.m. EDT on May 24, 2007.

aircraft fly odd thousands of feet while westbound traffic fly even thousands of feet.

Figure 2 shows the wind-optimal trajectories for the eastbound flights at 37,000 feet at 6 a.m. EDT on May 24, 2007. Blue polygons depict the areas favorable to persistent contrails formation. The trajectory computations are done using traffic and atmospheric data in the continental United States for May 4, May 24, and May 27 in 2007. The data for wind speed and direction are obtained from Rapid Update Cycle (RUC). For a specific scenario involving traffic operations and atmospheric conditions corresponding to May 27, 2007, a minimum fuel (equivalent to minimum CO_2 emissions) strategy results in 493 minutes travel through contrail regions [9]. The amount of contrail formation can be reduced either by flying around the potential contrail regions at the same cruise altitude (2D approach) or by changing the cruise altitude and going around the potential contrail regions (3D approach). Figure 3 shows the amount of additional fuel consumption, with the associated additional CO_2 emissions, needed to reduce travel through contrail regions by different amounts using 2D and 3D approaches. The 3D approach results in a larger reduction in the amount of contrails formed for the same amount of extra fuel above the baseline.

The amount of additional fuel consumed in flying a contrail reduction route instead of flying a wind optimal route represents increased

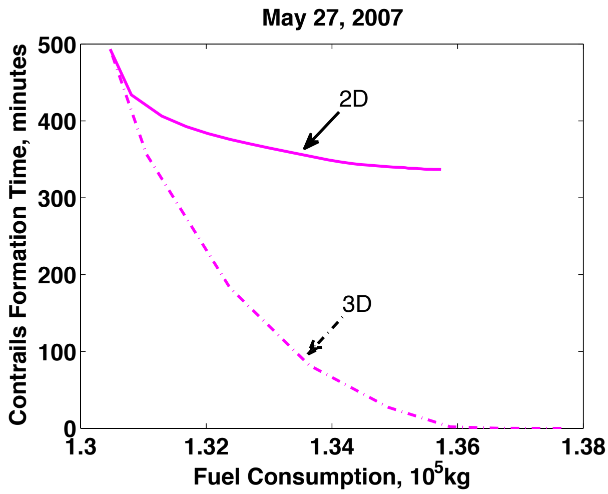


Fig 3. Trade-off curves between fuel consumption and contrail avoidance.

cost to the airlines as well as a negative impact on the environment due to the resulting excess CO_2 emissions. Each additional kg of fuel produces approximately 3.15kg of CO_2. Assuming a contrail cloud of finite width and a maximum contrail age of 6 to 24 hours, the contrail formation time in minutes can be converted into contrail formation in km depending on the aircraft speed. The use of AGTP provides a way to express the combined environmental cost of CO_2 emissions and contrails as a function of the fuel cost. Assuming, initially, that the radiative forcing due to contrails is independent of the location of the contrails, the difference in the near surface temperature between wind-optimal (fuel efficient) operations and contrail reduction operations can be approximated as

$$\Delta T = \Delta TCO_2 + \Delta TCon,$$

where ΔTCO_2 is the contribution to AGTP from CO_2 emissions and is equal to α times additional CO_2 emissions in kg produced over wind optimal route, ΔTCon is the contribution to AGTP from contrails and is equal to β times contrail formation in km. The values of α and β depend on the linear models for radiative forcing, the specific forcing due to CO_2, energy forcing due to contrails, energy balance model and the duration of the climate effect horizon [9]. The units for ΔT, α and β are degrees K, K/kg and K/km.

The CO_2 emissions produced by the aircraft are gradually absorbed by the atmosphere and the radiative forcing for CO_2 emissions is made of a steady state component and three exponentially decaying components with a specific forcing, $=1.82\times10^{-15}$ Wm^{-2}/kg of CO_2, a value taken from past studies [10]. The radiative forcing associated with contrails can be expressed similarly. However, an alternative way of expressing the impact of contrails on climate, Energy Forcing (EF)[11], is more useful in describing the net energy flux change due to a single flight over the lifetime of the contrails. Estimates of EF given the RF forcing due to contrails are described in [11]. The EF is expressed as joules/km of contrails. Table 2 shows the values of α and β for planning intervals of 25, 50 and 100 years. Estimates for the values for α and β and their dependency on the various uncertainties in climate and emission modeling are described in the next section.

Looking at a horizon of 50 years and a nominal value of EF=100GJ, a kg of fuel results in a temperature change of 1.82×10^{-15}K and a km of contrails results in a temperature change of 6.98×10^{-15}K. Using nominal values for α and β, the data in Figure 3 is represented in Figure 4 as a trade-off between fuel cost and environmental impact of rerouting expressed as changes to the Earth's surface temperature. Figure 4 shows AGTP, for H=25 years and EF=100GJ, as a function of the amount of fuel used for different two and three-dimensional contrail reduction strategies. The contribution to AGTP from CO_2 emissions increases linearly with fuel consumption and the contribution due to contrails is nonlinear. The cumulative AGTP curve decreases initially with reduction in contribution from contrails and eventually offset by the increase in contribution from CO_2 emissions. The curves show that even if the cost of fuel is not taken into consideration, under certain conditions, reducing contrails beyond a certain level may neither be economical nor good environmental policy.

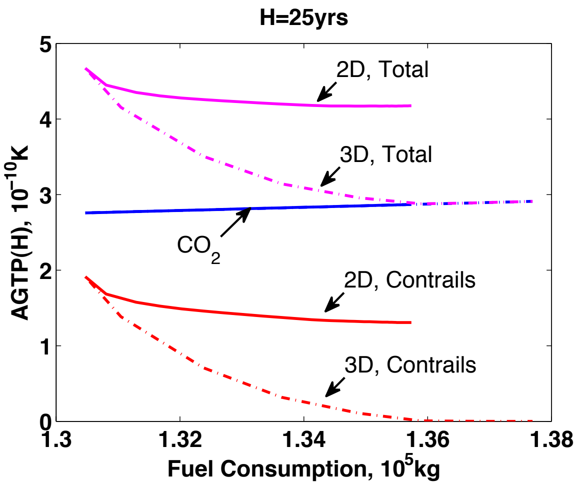


Fig 4. Trade-off curves in terms of AGTP.

3 Uncertainty Quantification

The trade-off curves in Figure 4 between fuel cost and changes to the Earth's surface temperature depend on several parameters. The uncertainties associated with each parameter can be described variously either by distributions, intervals or expert opinion. Uncertainties associated with aircraft parameters can be described by probability distributions, whereas climate impacts of emission are available as intervals. Uncertainty associated with the cost of a unit of CO_2 emissions is based on expert opinion, and those associated with the targets for emissions are still in flux. Error bounds on the performance of the system can be computed by considering several different uncertainties such as daily variations, aircraft weight uncertainties, size of the contrail regions based on relative humidity, coverage of a single aircraft track, effect of wind variations and radiative forcing associated with contrails. This section captures the uncertainty associated with some of these parameters.

3.1 Uncertainty about the amount of aviation byproduct

This paper considers only the two major byproducts of aviation, CO_2 emissions and contrails in the following analysis. The effect of other greenhouse gases can be included in the analysis similarly. Compared to contrails, there are small errors in the estimate of CO_2 emitted by an aircraft. The amount of CO_2 emitted is directly proportional to fuel burn and varies with aircraft attitude, altitude and cruise speed. The emission estimates tend to be less accurate during climb and descent.

Line-shaped contrails or linear contrails (LC) form behind aircraft and persist under certain atmospheric conditions. Linear contrails (LC) that form behind aircraft spread into irregularly shaped cirrus-like clouds in favorable atmospheric conditions indistinguishable from natural cirrus. LC together with their spread is referred to as Contrail cirrus (CC). The cirrus properties are affected by aircraft soot emissions. The term Aviation Induced Cloudiness (AIC) includes CC and changes in cirrus properties or formation due to aircraft soot emissions. The formations of persistent linear contrails depend on atmospheric parameters and there are errors associated with estimates of relative humidity with respect to Water (RHW) in numerical weather models. RUC underestimates upper tropospheric humidity. This is corrected in some models by predicting the onset of persistence contrails at a lower Relative humidity with respect to ice (RHI) than 100% (e.g., 85%). Although, a lower value of RHI increases the area of contrail coverage, it does not affect the overall pattern of contrail coverage in the US. A preliminary analysis of the effect of relative humidity errors on the trade-off curves is presented in [7].

Atmospheric parameters, temperature and relative humidity, vary both on a diurnal and seasonal basis. These parameters affect the location of regions favorable to persistent contrail formation. As an example, the daily variation in the contrail formation time for wind optimal flights for the special set of 12 city-pair routes during the month of May 2007 is shown in Figure 5. To reduce the amount of computations, three days are selected from the month of May 2007 representing a day with high contrails (HCD), a day with medium amount of contrails (MCD) and a day with low amount of contrails (LCD). These three days, HCD, MCD and LCD, will be used to represent variations in atmospheric conditions. Figure 6 shows how the trade-off between contrail formation time and additional fuel consumption varies for the same traffic scenario for atmospheric conditions corresponding to low (May 24), medium (May 4) and high (May 27) contrail formation days. Full lines and dotted lines show the reduction in contrails using 2D approach and 3D approach respectively.

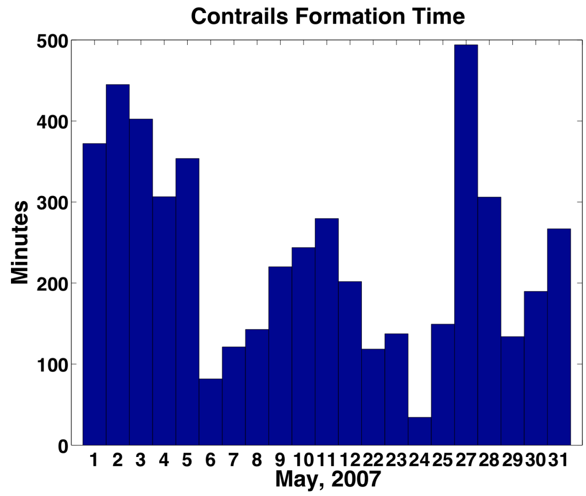


Fig 5. Contrail formation during May 2007.

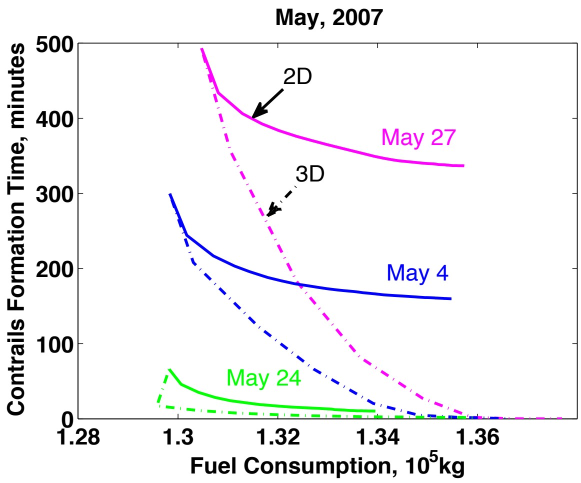


Fig 6. Trade-off between contrail formation time and additional fuel consumption on different days.

3.2 Radiative Forcing (RF)

The RF resulting from all aviation sources was estimated to be 50 mW/m^2 in 1992 (about 3.5% of all anthropogenic RF) and projected to be 190 mW/m^2 in 2050 [12]. The value varied from 130-560 mW/m^2 for a full range of scenarios. The IPCC estimated that the RF from CO_2 due to aviation in the range 13-26 mW/m^2 with a mean value of 18mW/m^2 [13]. More recently, it has been estimated to be around 30 mW/m^2.

It is essential to develop and validate models to predict the physical and radiative properties of contrails from the RUC and other numerical weather models. The persistence contrail formation for the continental United States correlates well with the 4-km imagery from Geostationary Operational Environmental Satellite (GOES-8). The RF associated with contrails depends on the area, optical thickness and the lifetime of the contrails. The first estimates of RF for the year 1992, 20 mW/m^2, were based on [14]. The IPCC revised the estimates, based on a better understanding of the optical depth of contrails, to 10mW/m^2 with an uncertainty range of [6,15] mW/m^2 [15]. The IPCC acknowledged the effect of CC to be large. However, it did not estimate the RF due to CC due to the large uncertainty associated with it. It is argued that a large fraction of CC is optically very thin and thus can neither be detected by a satellite nor visible from ground. Recent research [16], using a contrail-cirrus module global climate model ECHAM4, has indicated that the RF due to contrail cirrus is about 9 times larger than that from LC. This makes CC with a RF of 31mW/m^2 as the single biggest source of aviation induced RF.

The estimates of EF are made by assuming a mean value for RF resulting from contrails due to the entire distance flown by the aviation fleet during a year. Assuming a RF=10mW/m^2 and a total distance flown by the entire civil aviation fleet annually as 3.3×10^{10}km, the RF due to LC per km of flight = 3.0×10^{-10} mW/m^2/km. However, 1250km flight observations with a single aircraft operating in conditions favorable for PC appears to exert a contrail-induced RF some 5000 times greater (1.6×10^{-6}mW/m^2/km) than recent estimates of the average LC RF from the entire civil aviation fleet [17].

3.3 Energy Balance Models

The computation of AGTP assumes simple linear climate/energy balance models to compute the changes in the surface temperature due to the changes in the RF of greenhouse gases and contrails. The change to the Earth's surface temperature, an end-point metric, is expressed as the change at the end of a planning interval. CO_2 has a lifetime extending over hundreds of years, while the lifetime of contrails varies over a few hours. Due to the different lifetimes associated with CO_2 emissions and contrails, their contribution to the temperature change is strongly influenced by the time horizon (H). The planning interval is influenced by policy-making and time horizons ranging from 25 to 100 years are considered in this paper.

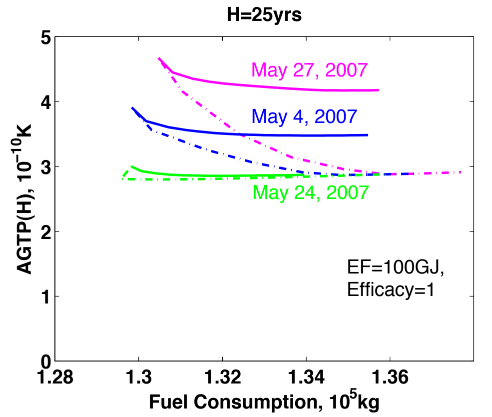
The efficacy factor is used differentiate the way radiative forcing from CO_2 and contrails affect the climate. It is defined as the ratio between the global temperature increase for a local energy input relative to that for a CO_2-equivalent globally distributed energy input [10]. The efficacy factor for annual mean contrail cover is estimated to be about 0.6 [18]. The efficacy factor is treated as a parameter in this paper and its value is in the range [0.6 - 1.0]. The shape of trade-off curves in Figure 4 depends on several parameters. The efficacy factor is used differentiate the way radiative forcing from CO_2 and contrails affect the climate. It is defined as the ratio between the global temperature increase for a local energy input relative to that for a CO_2-equivalent globally distributed energy input [10]. The efficacy factor for annual mean contrail cover is estimated to be about 0.6 [18]. The efficacy factor is treated as a parameter in this paper and its value is in the range [0.6 - 1.0].

4 Results

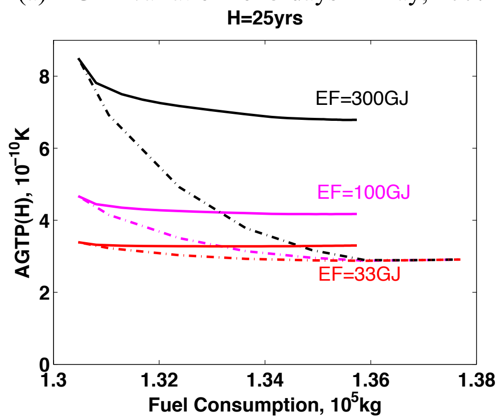
This section describes results based on several scenarios using discrete values in the range of different important parameters affecting the impact of aviation on climate. Figure 7.a shows the variation of AGTP with fuel consumption for three different days in May 2007. The results are shown for H=25 years, EF=100GJ and efficacy=1.0. The changes to AGTP using route only optimization (2D) are indicated by solid lines while changes involving additional altitude changes (3D) are shown by dash-dotted lines. For all days, contrail reduction maneuvers involving altitude changes produce more fuel efficient results, measured as decrease in AGTP for unit amount of fuel, than just horizontal maneuvers. On May 27, an additional 4000 kg (about 2-3% additional fuel usage of fuel reduces AGTP to its lowest value with no further reduction possible. Any reduction in contrails beyond this point is negated by the increase in CO_2 emissions. Again, the same trend holds on all days. However, the reduction in AGTP due to contrail reduction maneuvers is minimal on days with low amounts of contrail formation. These results suggest that to limit the amount of excess fuel usage while minimizing the environmental impact of aviation operations, it is cost-beneficial to do no contrail reduction maneuvers on days with low amount of contrail formation. These are significant observations for the development of operational strategies to reduce the impact of aviation on climate. The next paragraph examines if these results are valid in the presence of various uncertainties.

A major source of uncertainty is the RF values associated with contrails. As discussed earlier, these values range from 10 to 90 mW/m^2 depending on various assumptions about contrail formation and its spreading. Three different values, 10, 30 and 90 mW/m^2, are used in this study. The three RF values for contrails translate into equivalent EF values, 33, 100 and 300GJ. Figure 7.b shows the influence of the variation in RF estimates of contrails for three different values of EF on May 27. Although, higher values of EF result in net bigger reductions of AGTP, the reductions level off more or less at about the same amount of extra fuel consumption.

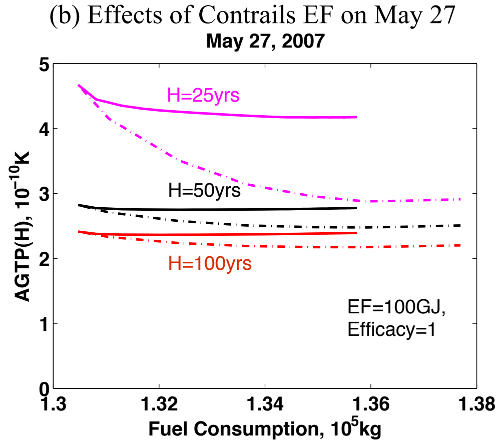
Being an end point metric, the value of AGTP is heavily influenced by the choice of policy horizon. For May 27 with EF=100GJ and efficacy=1.0, Figure 7.c shows the same trade-off curves for three different values of H=25, 50



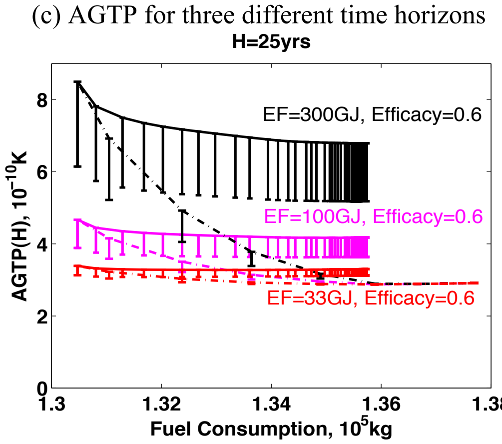
(a) AGTP variation for 3 days in May, 2007



(b) Effects of Contrails EF on May 27



(c) AGTP for three different time horizons



(d) Efficacy factors between 0.6 and 1.0

Fig 7. Variation of AGTP with fuel consumption for three different days in May 2007 and 100 years. The small lifetime of contrails compared to the lifetime of CO_2 reduces the contrail contribution to AGTP significantly as H increases, with approximately a six-fold reduction from 25 to 100 years. The behavior of AGTP with increasing contrail reduction maneuvers tapers off at approximately the same amount of extra fuel usage as in the earlier cases.

The AGTP curves for contrail reduction using horizontal maneuvers for different values of EF described in Figure 7.b are recomputed for various values of efficacy. The effect of varying efficacy in the range [0.6-1.0] is shown in Figure 7.d. Lower values of efficacy result in lower values of AGTP under all conditions. However, the overall trend in the relationship between fuel usage and the impact of contrail reducing maneuvers remains unchanged.

5 Summary and Conclusions

This paper brings together the modeling of complex aeronautical system behavior and interactions with climate science involving widely varying time (minutes to years) and spatial scales (local to world-wide). The main contributions of the paper are: (a) the integration of simplified models, real weather and traffic data, multiple scenarios and error bounds in a process that can be used to guide operational solutions to reduce the impact of aviation on climate, (b) innovative use of contrail frequency index, a measure of the potential for a specific set of traffic and atmospheric conditions to produce persistent contrails, to reduce the number of computations and (c) the quantification of variation in the fuel cost versus surface temperature reduction curves due to limitations in the modeling of contrail formation, radiative forcing associated with contrails and energy balance models. An important conclusion from the study is that contrail reduction maneuvers involving altitude changes produces more fuel efficient results, measured as decrease in surface temperature change for unit amount of fuel, than just horizontal maneuvers. A 2-3% additional fuel usage reduces the surface temperature change to its lowest value. Any reduction in contrails beyond this point is negated by the increase in CO_2 emissions. The results suggest that to limit the amount of excess fuel usage while minimizing the environmental impact of aviation operations, it is cost-beneficial to limit contrail reduction maneuvers to days with medium or high amount of contrail formation. These characteristics seem to be true even in the presence of various uncertainties. These conclusions are based on limited traffic scenarios and assume that the effect of contrails is independent of their location. These limitations can be removed by using a larger number of traffic scenarios and using more detailed contrail models. The quantification results based on this paper can be included in the FAA national policy development tools like Aviation Environmental Design Tool and Aviation Environmental Portfolio Management Tool (APMT) [14].

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